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Title:
TRAINS OF ABLATION PULSES FROM MULTIPLE OPTICAL AMPLIFIERS

Abstract:
The present invention provides various method of ablative material removal from an object. One such method uses a short optical pulse that is stretched amplified and then compressed by generating an initial sub-picosecond pulse in a semiconductor pulse generator and time-stretching the initial pulse, amplifying the stretched pulse and then compressing the amplified pulse, wherein the amplifying and compression are done with either a optically-pumped-amplifier and air-path between gratings compressor combination, or a SOA and chirped optically-pumped compressor combination, wherein more than one amplifiers are used in parallel, and pulses are timed to arrive at the surface from 1 to 50 nanoseconds apart, and applying the compressed optical pulse to the object.

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(54) **Title:** TRAINS OF ABLATION PULSES FROM MULTIPLE OPTICAL AMPLIFIERS

(57) **Abstract:** The present invention provides various method of ablative material removal from an object. One such method uses a short optical pulse that is stretched amplified and then compressed by generating an initial sub-picosecond pulse in a semiconductor pulse generator and time-stretching the initial pulse, amplifying the stretched pulse and then compressing the amplified pulse, wherein the amplifying and compression are done with either a optically-pumped-amplifier and air-path between gratings compressor combination, or a SOA and chirped optically-pumped compressor combination, wherein more than one amplifiers are used in parallel, and pulses are timed to arrive at the surface from 1 to 50 nanoseconds apart, and applying the compressed optical pulse to the object.

TRAINS OF ABLATION PULSES FROM MULTIPLE OPTICAL AMPLIFIERS

This patent application claims priority to the following previously filed United States provisional patent applications:

Docket Number	Title	US Serial Number	Filing Date
ABI-1	Laser Machining	60/471,922	05/20/2003
ABI-7	Stretched Optical Pulse Amplification and Compression	60/471,971	05/20/2003
ABI-23	Controlling Optically-Pumped Optical Pulse Amplifiers	60/503,578	09/17/2003

Technical Field

The present invention relates in general to the field of light amplification and, more particularly, to trains of ablation pulses from multiple optical amplifiers.

Background Art

Ablative material removal is especially useful for medical purposes, either in-vivo or on the outside surface (e.g., skin or tooth), as it is essentially non-thermal and generally painless. Moreover, ablative material removal essentially exerts no pressure on the surface of the material, so it is quite useful for many other types of cutting and machining. Ablative material removal is generally done with a short optical pulse that is stretched amplified and then compressed. A number of types of laser amplifiers have been used for the amplification, including fiber amplifiers. Fiber amplifiers have a storage lifetime of about 100 to 300 microseconds. While some measurements have been made at higher repetition rates, these measurements have shown an approximately linear decrease in pulse energy. For ablations purposes, fiber amplifiers have been operated with a time between pulses of equal to or greater than the storage lifetime, and thus are generally run a repetition rate of less than 3-10 kHz.

Laser ablation is very efficiently done with a beam of very short pulses (generally a pulse-duration of three picoseconds or less). While some laser machining melts portions of the work-piece, this type of material removal is ablative, disassociating the surface atoms. Techniques for generating these ultra-short pulses are described, e.g., in a book entitled "Femtosecond Laser Pulses" (C. Rulliere – editor), published 1998, Springer-Verlag Berlin Heidelberg New York. Generally large systems, such as Ti:Sapphire, are used for generating ultra-short pulses (USP). When high-power pulses are desired, they are often

intentionally lengthened before amplification to avoid thermally-induced internal component optical damage.

USP phenomenon was first observed in the 1970's, when it was discovered that mode-locking a broad-spectrum laser could produce ultra-short pulses. The minimum pulse duration attainable is limited by the bandwidth of the gain medium, which is inversely proportional to this minimal or Fourier-transform-limited pulse duration. Mode-locked pulses are typically very short and will spread (*i.e.*, undergo temporal dispersion) as they traverse any medium. Subsequent pulse-compression techniques are often used to obtain USP's. Pulse dispersion can occur within the laser cavity so that compression techniques are sometimes added intra-cavity. Previous approaches have generally operated maximum-sized amplifiers at maximum power and amplified longer and longer pulses. When high-power pulses are desired, they are intentionally lengthened before amplification to avoid internal component optical damage. This is referred to as "Chirped Pulse Amplification" (CPA). The pulse is subsequently compressed to obtain a high peak power (*pulse-energy amplification* and *pulse-duration compression*).

Summary of the Invention

It has been found that ablative material removal with a very short optical pulse is especially useful for medical purposes and can be done either in-vivo or on the body surface, as it is essentially non-thermal and generally painless. Typically the surgical ablation event has a threshold of less than 1 Joule per square centimeter, but occasionally removal of foreign material may require dealing with an ablation threshold of up to about 2 Joules per square centimeter. Thus control of pulse energy density is desirable. It has been found that in optically-pumped amplifiers, this can be done by controlling repetition rate and can be fine-tuned by controlling optical pumping power. In addition, some materials ablate much faster than others and control of the ablation rate is also desirable. Further, it is preferred that ablation rate be controllable independent of pulse energy. The use of more than one amplifier in parallel a train mode (pulses from one amplifier being delayed to arrive one or more nanoseconds after those from another amplifier) allows step-wise control of ablation rate independent of pulse energy density. At lower desired ablation rates, one or more amplifiers can be shut down.

Likewise, the present invention can be used for ablation laser-machining wherein at least one 0.01 to 10 microsecond-long train of pulses are generated. Each pulse has a

pulse-duration of 50 femtoseconds to three picoseconds with the pulses being at intervals of 1 to 20 nanoseconds.

The use of parallel amplifiers in either type of system provides faster ablation, while providing greater cooling surface area to minimize thermal problems. In addition, one or more of the parallel amplifiers can be shut down, allowing more efficient ablation of a variety of materials with different ablation thresholds, as surfaces are most efficiently ablated at an energy density about three times threshold.

The use more than one amplifier in parallel a train mode (pulses from one amplifier being delayed to arrive one or more nanoseconds, after those from another amplifier) allows step-wise control of ablation rate independent of pulse energy. Pulses may also arrive one or more picoseconds after those from another amplifier. For increased efficiency at lower desired ablation rates, one or more amplifiers can be shut off (e.g. the optical pumping to a optically-pumped amplifier), and there will be fewer pulses per train. Thus with 20 amplifiers there would be a maximum of 20 pulses in a train, but many embodiments might use only three or four amplifiers and three or four pulses per train.

While quasi-CW operation might generally be used in each operating amplifier, in some embodiments multiple amplifiers might be run in a staggered fashion, e.g. ON for a first period (of one second or more) and then turned OFF for a second period (again of one or more seconds), and a first period dormant amplifier turned ON during the second period, and so forth, to spread the heat load. Thus the use of multiple amplifiers with pulses slightly staggered in time increases control flexibility and increases efficiency.

The present invention provides a method of ablative material removal from an object, with a short optical pulse that is stretched amplified and then compressed by generating an initial sub-picosecond pulse in a semiconductor pulse generator (e.g. within a man-portable system) and time-stretching the initial pulse, amplifying the stretched pulse and then compressing the amplified pulse, (e.g. wherein the amplifying and compression are done with either a optically-pumped-amplifier and air-path between gratings compressor combination, or a SOA and chirped optically-pumped compressor combination), wherein more than one amplifiers are used in parallel, and pulses are timed to arrive at the object from 1 to 50 nanoseconds apart, and applying the compressed optical pulse to said object. In many applications, material is successively removed from a surface and surfaces exposed by prior removal to create a hole through the object.

The amplifying and compressing is done with an optically-pumped-amplifier and air-path between gratings compressor combination, and the sub-picosecond pulses are stretched to between 500 picoseconds and three nanoseconds. More than two optically-pumped (Cr:YAG) amplifiers or more than two semiconductor optical amplifiers may be used in parallel. More than one optically-pumped amplifiers may be used with one compressor. In some embodiments, a first set of at least two pulses is timed to arrive at the surface within a 1 to 100 picoseconds time period, and/or a second set of at least two pulses is timed to arrive at the surface 1 to 25 nanoseconds after the first set of pulses.

In addition, the present invention provides a method of ablative material removal, from a surface by generating an initial sub-picosecond pulses in a semiconductor pulse generator and time-stretching the initial pulse, amplifying the stretched pulses, and then compressing the amplified pulses, wherein more than one amplifiers are used in parallel, and applying the compressed optical pulse to the surface, wherein the compressed pulses from the more than one amplifiers used in parallel are timed to arrive at the surface from 1 to 50 nanoseconds apart.

Preferably, pulse energy density and ablation rate are independently controlled. A set of pulses may be timed to arrive at the surface within a 5 to 50 picoseconds period, and/or pulses within a set of pulses are timed to arrive at the surface from 20 to 50 picoseconds apart.

In addition, the present invention provides a method of ablative material removal from an object by using more than one amplifiers in parallel to amplify optical pulses, and applying the amplified optical pulse to the object, wherein the pulses from the more than one amplifiers used in parallel are timed to arrive at the object from 1 to 50 nanoseconds apart.

Moreover, the present invention provides a method of ablation laser-machining by generating a train of pulses with more than one amplifier, (e.g. with each pulse having a pulse-duration of 50 femtoseconds to three picoseconds), with the pulses being at intervals of 1 to 50 nanoseconds, and directing a beam of the pulses to an object (e.g. a work-piece) with a pulse-energy-density of 0.1 to 20 Joules/square centimeter to produce at least one hole in the work-piece. Preferably the hole penetrates through the work-piece. Such machining makes the laser-machining relatively vibration-resistant.

The amplifying and compressing can be done with a optically-pumped-amplifier and air-path between gratings compressor combination, e.g., with the sub-picosecond

pulses stretched to between 10 picoseconds and one nanosecond, or the amplifying and compressing can be done with a chirped optically-pumped compressor combination, e.g., with the sub-picosecond pulses stretched to between 1 and 20 nanoseconds. In some embodiments the man-portable system comprises a wheeled cart or a backpack. In some embodiments, the optically-pumped amplifier is a Cr:YAG amplifier or an erbium-doped fiber amplifier, and the air-path between gratings compressor preferably is a Treacy grating compressor. Thus, more than one optically-pumped amplifiers are used in parallel, or more than one semiconductor optical amplifiers are used in parallel. More than one optically-pumped amplifiers may be used with one compressor.

The present invention also provides a method of ablative material removal, from a surface with a short optical pulse that is stretched amplified and then compressed by generating an initial sub-picosecond pulse in a semiconductor pulse generator and time-stretching the initial pulse, amplifying the stretched pulse and then compressing the amplified pulse, wherein the amplifying and compression are done with either a optically-pumped-amplifier, or a SOA, and wherein more than one amplifiers are used in parallel, and wherein pulses are timed to arrive at the surface from 1 to 50 nanoseconds apart, and applying the compressed optical pulse to the surface.

High ablative pulse repetition rates are preferred and the total pulses per second (the total system repetition rate) from the one or more parallel optical amplifiers is preferably greater than 0.6 million.

Brief Description of the Drawings

No Figures.

Description of the Invention

While the making and using of various embodiments of the present invention are discussed in detail below, it should be appreciated that the present invention provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and use the invention and do not delimit the scope of the invention.

To facilitate the understanding of this invention, a number of terms are defined below. Terms defined herein have meanings as commonly understood by a person of ordinary skill in the areas relevant to the present invention. Terms such as "a", "an" and "the" are not intended to refer to only a singular entity, but include the general class of

which a specific example may be used for illustration. The terminology herein is used to describe specific embodiments of the invention, but their usage does not delimit the invention, except as outlined in the claims.

Ablative material removal with a very short optical pulse is especially useful for many purposes. It has been found, for example, that ablation-type laser-machining can be made vibration-resistant by using a train of pulses from multiple parallel (train-mode amplifiers, each pulse having a pulse-duration of 50 femtoseconds to three picoseconds, with the pulses being at intervals of 1 to 50 nanoseconds. This may be used reliably produce a series of holes in a work-piece. Perforations (adjacent holes through the work-piece) can be produced to allow removal of a portion of the work-piece. The control of pulse energy is desirable. It has been found that in optically-pumped amplifiers, this can be done step-wise by controlling repetition rate and can be fine-tuned by controlling optical pumping power. In addition, some materials ablate much faster than others and control of the ablation rate is also desirable. Further, it is preferred that ablation rate be controllable independent of pulse energy. It has been further found that the use more than one amplifier in parallel a train mode (pulses from one amplifier being delayed to arrive one or more picoseconds, or more nanoseconds, after those from another amplifier), also allows step-wise control of ablation rate independent of pulse energy. Thus the use more than one amplifier in parallel a train mode not only allows vibration-resistant machining, but also allows step-wise control of ablation rate independent of pulse energy.

It has been found that two laser-amplifier/compressor combinations enable practical, and significant size reduction, which in turn enables the system to be man-portable. A used herein, the term "man-portable" means capable of being moved reasonably easily by one person, e.g., as wheeling a wheeled cart from room to room or possibly even being carried in a backpack. In one embodiment, the present invention uses sub-picosecond pulses stretched to between 10 picoseconds and one nanosecond, with the stretched pulse either amplified by a fiber-amplifier (e.g., a erbium-doped fiber amplifier or EDFA) and compressed by an air-path between gratings compressor (e.g., a Treacy grating compressor), with the compression creating a sub-picosecond ablation pulse. Alternately, the present invention uses a semiconductor optical amplifier (SOA) and a with a chirped fiber compressor, generally with pulses stretched to 1 to 20 nanosecond during amplification. Generally, the present invention uses a semiconductor generated initial sub-picosecond pulse in either case and preferably a chirped fiber stretcher in either case (to

reduce system size for man-portability), and preferably uses a SOA preamplifier to amplify the initial pulse before introduction into the fiber amplifier.

Laser machining is most efficiently done with a beam of very short pulses (generally a pulse-duration of three picoseconds or less) in a controlled range of energy density (generally about 0.1 to 20 Joules/square centimeter, and preferably 0.1 to 8 Joules/square centimeter). While lasers can remove a slit of material, e.g., 500 microns wide, it has been found that most cutting tasks on most materials (including metals), can be much more efficiently done as a line of small diameter perforations (e.g., 25 micron holes on 40 micron centers), which allows the material to break cleanly along the line with little or no application of additional force. Thus, the amount of material that needs to be removed is greatly reduced and the small spot size reduces the required power and allows machining with smaller and less expensive lasers (including portable semiconductor-chip-diode systems). Perforation machining with tapered holes is also much more practical as channeling of the energy within a hole generally causes the hole diameter to taper down with depth (while the hole diameter can be made relatively constant, this is generally unnecessary and consumes more energy).

It has also been found that with the controlled energy density, however, that in many instances, holes formed by a single pulse (and often even several pulses) do not sufficiently penetrate the work-piece to give a clean break. Further, due to the small diameter of the laser beam, relative motion (e.g., vibration) between the laser beam and the work-piece can prevent successive pulses from hitting the same hole, thus preventing sufficient penetration. Even in other laser machining, e.g., when the surface is being ablated, rather than a hole produced, movement such as vibration can cause uneven ablation. Note that other uses such as surgical procedures can use surface ablation or cutting, and can use overlapping ablation to produce a cut surface, rather than a series of holes. In all such uses, a train of pulses is preferably generated by one or more semiconductor-chip diodes. Note also, the train of pulses allows a quasi-continuous wave operation that improves system efficiency, e.g., lessening the number of power up-ramps and down-ramps.

Typically a line of laser-produced holes (including a circle of small holes to create a large hole) is desired. There are, however, applications where a single laser-produced hole completely penetrating a work-piece is desired. Again, vibration or other motion can interfere with efficient production of such a hole.

It has also been found that the smaller and less expensive lasers (e.g., semiconductor-chip diodes) can generate a train of femtosecond pulses at intervals of a few nanoseconds for up to a few microseconds without overheating. As there are generally only a few nanoseconds between the pulses, and as channeling guides energy down the hole even if the beam and hole centerlines are offset by a few microns, relative motion would have to be many times supersonic to prevent multiple pulses from entering each laser-produced hole.

One embodiment of the present invention provides a method of perforation laser-machining that includes generating at least one 0.01 to 10 microsecond-long train of pulses, each pulse having a pulse-duration of 50 femtoseconds to three picoseconds, with said pulses being at intervals of 1 to 20 nanoseconds, and directing a beam of said pulses to a work-piece with a pulse-energy-density of 0.1 to 20 Joules/square centimeter to produce one or more holes in the work-piece. The holes may be, e.g., 10 to 150 micron holes on centers 15 to 300 microns. Preferably, the train of pulses are 0.05 to 1 microsecond-long; the pulse-duration is 50 femtoseconds to 1 picoseconds; pulses at intervals are 1 to 10 nanoseconds; and the pulse-energy-density is between 1 and 8 Joules/square centimeter on the work-piece. The holes are preferably 20 to 100 micron holes on centers 15 to 200 microns.

For example, a 100 femtosecond pulse can be time-stretched to make an optical pulse signal ramp (of, e.g., increasing, wavelength) which is amplified (at comparatively low instantaneous power), and time-compressed into an amplified 100 femtosecond pulse. Generally a series of pulses are generated, and thus a series of wavelength-ramps are used (e.g., a "saw-tooth" waveform with 50 "teeth" may be amplified by the SOAs without turning the current off between the teeth). Thus although the amplifiers are amplifying continuously during the 50-tooth waveform, the time-compression will separate the optical output into 50 separate pulses.

Semiconductor laser diodes are highly preferred for generating the ultra-short pulses. Semiconductor laser diodes typically are of III-V compounds (composed of one or more elements from the third column of the periodic table and one or more elements from the fifth column of the periodic table, e.g., GsAs, AlGaAs, InP, InGaAs, or InGaAsP). Other materials, such as II-VI compounds, e.g., ZnSe, can also be used. Typically lasers are made up of layers of different III-V compounds (generally, the core layer has higher index of refraction than the cladding layers to generally confine the light to a core).

Semiconductor lasers have been described (see Rulliere, Chapter 5). It should be noted that this method works especially with semiconductor-chip diodes. Semiconductor-chip diodes can have high efficiency (e.g., about 50%) and have short energy-storage-lifetimes (e.g., a few nanoseconds). With a small, e.g., 20 micron spot, the ablating energy can be furnished by a single semiconductor optical amplifier (SOA) putting out less than 10 micro-Joules per pulse (which low energy density also limits collateral damage). The other types of lasers (e.g., Ti:sapphire) generally have energy-storage-lifetimes (e.g., in the hundreds of microsecond range), and this is convenient for accumulating energy and releasing it in a short period of time as a high-energy pulse. These other type of lasers have generally been used for generating short, high energy pulses, but their efficiencies are low (generally less than 1%) and the pulse energies drop off rapidly when operated at high repetition rates (when they begin to heat up, and when time between pulses becomes short and starts to reduce the time for accumulating energy for the next pulse). Conversely, semiconductor-chip diodes can provide a microsecond long train of pulses of nearly constant energy with nanosecond spacings. Thus while other types of lasers could be used, semiconductor-chip diodes are preferred.

The examples used herein are to be viewed as illustrations rather than restrictions, and the invention is intended to be limited only by the claims. For example, the invention applies not only to GaAs and InP (which generates light within it III-V semiconductor structure at a wavelength of about 1550 nm) laser diodes, but also to other semiconductor materials such as II-VI compounds.

Ablation is most efficient at about three times the material's ablation threshold, and thus control of pulse energy density for optimum removal efficiency is very desirable. If the spot size is fixed or otherwise known, this can be achieved by controlling pulse energy; or if the pulse energy is known, by controlling spot size. The present invention uses a novel method of controlling the pulse energy by controlling the amplified pulse energy, which is much more convenient than changing the ablation spot size. It has been found that optically-pumped amplifiers are more effective operated at a fraction (e.g., less than about half) of their maximum stored energy. When operated in this manner, the pulse energy can be varied by controlling the repetition rate, as the amount of stored energy in the amplifier increases with the time between pulses.

It has been found that in fiber amplifiers, pulse energy control can be done step-wise by controlling repetition rate and can be fine-tuned by controlling optical pumping

power. The pulse energy of a semiconductor optical amplifier (SOA) can be adjusted by changing the current thru the amplifier.

While the compressors in either type of system can be run with inputs from more than one amplifier, reflections from other of the parallel amplifiers can cause a loss of efficiency, and thus should be minimized (as used herein, "parallel" includes train mode). The loss is especially important if the amplifiers are amplifying signals at the same time, as is the case with the SOAs. Thus each off the parallel SOAs preferably has its own compressor and while the amplified pulses may be put into a single fiber after the compressors, reflections from the joining (e.g., in a star connector) are greatly reduced before getting back to the amplifier. With the fiber amplifiers, however, a nanosecond spacing of sub-nanosecond stretched pulses eliminates any amplifying of multiple signals at the same time, and a single compressor is preferably used.

Fiber amplifiers have a storage lifetime of about 100 to 300 microseconds. While measurements have been made at higher repetition rates, these measurements have shown an approximately linear decrease in pulse energy. For ablations purposes, power fiber amplifiers have generally been operated with a time between pulses about equal to than the storage lifetime (or at greater than the storage lifetime, to avoid thermal problems in the fiber), and thus are generally run a repetition rate of less than 3-10 kHz. Optically-pumped amplifiers are available with average power of 30 W or more. A moderate-power 5 W average power optically-pumped amplifiers have been operated to give pulses of 500 microJoules or more, as energy densities above the ablation threshold are needed for non-thermal ablation, and increasing the energy in such a system, increases the ablation rate in either depth or allows larger areas of ablation or both. The present invention, however, generally runs the optically-pumped amplifier with a time between pulses of a fraction (e.g., one-half or less) of the storage lifetime and uses a smaller ablation spot. Preferably, the spot is less than about 50 microns in diameter, but the diameter can be 60 or 75 microns and with sufficient power per amplifier, possibly even more (spot sizes herein are given as circle diameter equivalents, a "50 micron" spot has the area of a 50 micron diameter circle, but the spot need not be round). The smaller spot is preferably scanned to get a larger effective ablation area.

The present invention also preferably uses parallel optically-pumped amplifiers to generate a train of pulses to increase the ablation rate by further increasing the effective repetition rate (while avoiding thermal problems and allowing control of ablation rate by

the use of a lesser number of operating optically-pumped amplifiers). The present invention may use a SOA preamplifier to amplify the initial pulse before splitting to drive multiple parallel optically-pumped amplifiers and another SOA before the introduction of the signal into each optically-pumped amplifier (which allows rapid shutting down of individual optically-pumped amplifiers). Further, the present invention generally operates with pulse energy densities at about three times the ablation threshold for greater ablation efficiency.

The use of a 1 nanosecond selected-pulse with an optically-pumped amplifier and air optical-compressor (e.g., a Tracey grating compressor) typically gives compression with ~40% losses. At less than 1 nanosecond, the losses in a Tracey grating compressor are generally lower. If the other-than-compression losses are 10%, 2 nanoJoules are needed from the amplifier to get 1 nanoJoule on the target. Preferably, for safety purposes, 1550 nm light is preferably used. The use of much greater than 1 nanosecond selected-pulses in an air optical-compressor, in the past, presented two problems; the difference in path length for the extremes of long and short wavelengths needs to be more 3 cm and thus the compressor is large and expensive and generally not man-portable, and the losses increase with a greater degree of compression.

The alternate configuration with a semiconductor optical amplifier (SOA) and a with a chirped fiber compressor, and with pulses stretched to 1 to 20 nanosecond during amplification is run at repetition rates with a time between pulses of more that the very short semiconductor storage lifetime. Preferably the present invention uses a semiconductor generated initial pulse. The present invention may use a SOA preamplifier to amplify the initial pulse before splitting to drive multiple amplifiers. The present invention preferably scans the ablation a smaller spot to get a larger effective ablation area, and in many cases the scanned spot is smaller than the above optically-pumped-amplifier case. In addition, the present invention preferably uses parallel amplifiers to generate a train of pulses to increase the ablation rate by further increasing the effective repetition rate (while avoiding thermal problems and allowing control of ablation rate by the use of a lesser number of operating amplifiers).

Generally the fiber amplifiers are optically-pumped CW (and are amplifying perhaps 100,000 times per second in 1 nanosecond pulses). Alternately, non-CW-pumping might be used in operating amplifiers, with amplifiers run in a staggered fashion, e.g., one on for a first half-second period and then turned off for a second half-second period, and

another amplifier, dormant during the first-period, turned on during the second period, and so forth, to spread the heat load.

In such systems, the present invention can control input optical signal power, optical pumping power of optically-pumped amplifiers, timing of input pulses, length of input pulses, and timing between start of optical pumping and start of optical signals to control pulse power, and average degree of energy storage in optically-pumped amplifier.

Many fiber amplifiers have a maximum power of 4 MW, and thus a 10-microJoule-ablation pulse could be as short as 2 picoseconds. Thus e.g., a 10 picosecond, 10 microJoule pulse, at 500 kHz (or 50 microJoule with 100 kHz), and, if heating becomes a problem, operating in a train mode and switching fiber amplifiers. Thus one might rotate the running of ten fiber amplifiers such that only five were operating at any one time (e.g., each on for 1/10th of a second and off for 1/10th of a second). Again one can have ten fiber amplifiers with time spaced inputs, e.g., by 1 nanosecond, to give a train of one to 10 pulses. With 5 W amplifiers operating at 100 kHz (and e.g., 50 microJoules) this could step between 100 kHz and 1 MHz. With 50% post-amplifier optical efficiency and 50 microJoules, to get 6 J/sq. cm on the target, the spot size would be about 20 microns.

Another alternative is to have 20 optically-pumped amplifiers with time spaced inputs, e.g., by 1 nanosecond, to give a train of one to 20 pulses. With 5 W amplifiers operating at 50 kHz (and e.g., 100 microJoules) this could step between 50 kHz and 1 MHz. With 50% post-amplifier optical efficiency and 100 microJoules, to get 6 J/sq. cm on the target, the spot size would be about 33 microns. The selected pulse might be 50 to 100 picoseconds long. A similar system with 15 optically-pumped amplifiers could step between 50 kHz and 750 kHz.

Another alternative is to have 10 optically-pumped amplifiers with time spaced inputs, e.g., by 1 nanosecond, to give a train of one to 20 pulses. With 5 W amplifiers operating at 20 kHz (and e.g., 250 microJoules) this could step between 20 kHz and 200 kHz. With 50% post-amplifier optical efficiency and 250 microJoules, to get 6 J/sq. cm on the target, the spot size would be about 50 microns. The selected pulse might be 100 to 250 picoseconds long. A similar system with 30 optically-pumped amplifiers could step between 20 kHz and 600 kHz.

Generally it is the pulse generator that controls the input repetition rate of the optically-pumped amplifiers to fine tune energy per pulse to about three times threshold (e.g., from 5 to 50, or 5 to 100, microJoules per pulse).

Another alternative is generating a sub-picosecond pulse and time-stretching that pulse within semiconductor pulse generator to give the wavelength-swept-with-time initial pulse for the fiber amplifier. Another alternative is to measure light leakage from the delivery fiber to get a feedback proportional to pulse power and/or energy for control purposes. Measurement of spot size, e.g., with a video camera, is useful, and can be done with a stationary spot, but is preferably done with a linear scan. Preferably, the spot is less than about 50 microns in diameter.

The camera is preferably of the "in-vivo" type using an optical fiber in a probe to convey an image back to, e.g., a vidicon-containing remote camera body. This is especially convenient with a handheld beam-emitting probe and can supply its own illumination. Other cameras using an optical fiber in a probe to convey an image back to a remote camera body, e.g., a vidicon-containing camera with a GRIN fiber lens, can also be used. Endoscope type cameras can also be used.

Smaller ablation areas may be scanned by moving the beam without moving the probe. Large areas may be scanned by moving the beam over a first area, and then stepping the probe to second portion of the large area and then scanning the beam over the second area, and so on. The scanning may be by beam deflecting mirrors mounted on piezoelectric actuators. Preferably the system actuators scan over a larger region but with the ablation beam only enabled to ablate portions with defined color and/or area. A combination of time and; area and/or color, can be preset, e.g., to allow evaluation after a prescribed time.

Ablative material removal is especially useful for medical purposes either in-vivo or on the body surface and typically has an ablation threshold of less than 1 Joule per square centimeter, but may occasionally require surgical removal of foreign material with an ablation threshold of up to about 2 Joules per square centimeter. The use of more than one amplifier in parallel train mode (pulses from one amplifier being delayed to arrive one or more nanoseconds after those from another amplifier. At lower desired powers, one or more amplifiers can be shut off (e.g., the optical pumping to a fiber amplifier), and there will be fewer pulses per train. Thus with 20 amplifiers there would be a maximum of 20 pulses in a train, but most uses might use only three or four amplifiers and three or four pulses per train. While CW operation might normally be used for operating amplifiers, amplifiers might be run for e.g., one second and then turned off and a dormant amplifier turned on to spread the heat load.

The present invention provides a method of system operation for surgical material removal from a body by optical-ablation with controlled pulse energy from a fiber amplifier by determining a size of a spot to be used by the system, wherein the spot is between 10 and 60 microns diameter; setting a repetition rate to give time between pulses of between ½ and 1/10th the storage time of the fiber amplifier into the system, inputting a pulse-energy-for-material-being-ablated signal into the system; controlling current through one or more fiber-amplifier pump diodes to give a pulse energy density applied to the body is between 2.5 and 3.6 times ablation threshold of the body portion being ablated, utilizing an optical oscillator in the generation of a series of wavelength-swept-with-time pulses, amplifying the wavelength-swept-with-time pulse with the fiber-amplifier, time-compressing the amplified pulse and illuminating the spot on a portion of the body with the time-compressed optical pulse; and scanning the spot over an area, whereby removal over the area is even due to the high repetition rate, while the pulse energy is at a near optimum efficiency level. Preferably the fiber-amplifier repetition rate is at least 0.6 million pulses per second. Preferably the ablation spot size is between 20 and 50 microns in diameter. In some preferred embodiments, the ablation spot size is between 20 and 40 microns in diameter.

Moreover, the present invention provides a method of surgical material removal from a body by optical-ablation with controlled pulse energy from a optically-pumped pulse amplifier by inputting a nominal spot size signal and a pulse-energy-for-material-being-ablated signal, utilizing an optical oscillator in the generation of a series of wavelength-swept-with-time pulses, primarily controlling pulse energy based on the pulse-energy-for-material-being-ablated signal by either selecting pulses from the oscillator generated series of wavelength-swept-with-time pulses, wherein the fraction of pulses selected can be controllably varied to give a selected pulse repetition rate that is a fraction of the oscillator repetition rate, or passing electrical current through at least one pump diode to generate pumping light, optically pumping the optically-pumped pulse amplifier with the pumping light, and controlling pump diode current; using an ablation spot-size sensor to measure the ablation spot size and dynamically adjusting either the fraction of pulses selected or the pump diode current for changes in ablation spot size from the nominal spot size, amplifying the wavelength-swept-with-time pulse with the fiber-amplifier, and time-compressing the amplified pulse and illuminating a portion of the body

with the time-compressed optical pulse, whereby controlling the pulse selection controls the pulse energy.

In one embodiment, repetition rate is used to control pulse energy, the pre-compression optical amplifier's temperature is controlled by, and an active mirror is used in the compressor with the amplification of the active mirror being controlled by current of the active mirror's pump-diodes.

Generally a semiconductor oscillator is used to generate pulses and in some embodiments a SOA preamplifier is used to amplify the selected pulses before introduction into the optically-pumped pulse amplifier. In one embodiment, sub-picosecond pulses of between 10 picoseconds and one nanosecond are used, followed by pulse selection, with the selected pulses amplified by a fiber-amplifier (e.g., a erbium-doped optically-pumped pulse amplifier or EDFA) and compressed by an air-path between gratings compressor (e.g., a Treacy grating compressor), with the compression creating a sub-picosecond ablation pulse.

Compressors could be run with overlapping inputs from more than one amplifier, but reflections from other of the parallel amplifiers can cause a loss of efficiency. With the optically-pumped pulse amplifiers, a nanosecond spacing of sub-nanosecond pulses minimizes amplifying of multiple signals at the same time, and a single compressor is preferably used. High ablative pulse repetition rates are preferred and the total pulses per second (the total system repetition rate) from the one or more parallel optical amplifiers is preferably greater than 0.6 million.

Note also that optically-pumped optical pulse amplifiers (including, and those used to pump other optical devices) in general (including, and in such shapes as slabs, discs, and rods) can be controlled. Note further that lamp-pumped can be controlled by controlling the pumping lamps in a manner similar to that of controlling pump diode current. Preferably, active-diode diode pump-current is used to control the amplification of an active mirror. Generally optical pump device (diode or lamp) current is controlled either directly or indirectly by controlling voltage, power, and/or energy. As used herein, controlling current can include shutting off one or more optical pump devices, when multiple pump devices are used.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the

appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification, but only by the claims.

CLAIMS

1. A method of ablative material removal from an object, with a short optical pulse that is stretched amplified and then compressed, comprising the steps of:

generating an initial sub-picosecond pulse in a semiconductor pulse generator and time-stretching the initial pulse;

amplifying the stretched pulse and then compressing the amplified pulse, wherein the amplifying and compression are done with either a optically-pumped-amplifier and air-path between gratings compressor combination, or a SOA and chirped optically-pumped compressor combination, wherein more than one amplifiers are used in parallel, and pulses are timed to arrive at the surface from 1 to 50 nanoseconds apart; and

applying the compressed optical pulse to the object.

2. The method of claim 1, wherein material is successively removed from a surface, and surfaces exposed by prior removal, to create a hole through the object.

3. The method of claim 1, wherein more than two optically pumped amplifiers are used in parallel.

4. The method of claim 1, wherein more than two semiconductor optical amplifiers are used in parallel.

5. The method of claim 1, wherein more than one optically-pumped amplifiers are used with one compressor.

6. The method of claim 1, wherein a first set of at least two pulses is timed to arrive at the surface within a 1 to 100 picoseconds time period, and a second set of at least two pulses is timed to arrive at the surface 1 to 25 nanoseconds after the first set of pulses.

7. A method of ablative material removal from an object, comprising the steps of:

using more than one amplifiers in parallel to amplify optical pulses; and

applying the amplified optical pulse to the object, wherein the pulses from the more than one amplifiers used in parallel are timed to arrive at the object from 1 to 50 nanoseconds apart.

8. The method of claim 7, wherein more than one optically-pumped amplifiers are used with one compressor.

9. The method of claim 7, wherein pulse energy density and ablation rate are independently controlled.

10. The method of claim 7, wherein a set of pulses is timed to arrive at the surface within a 1 to 100 picoseconds period.

11. The method of claim 7, wherein a set of pulses is timed to arrive at the surface within a 5 to 50 picoseconds period.

12. The method of claim 10, wherein pulses within the set of pulses are timed to arrive at the surface from 20 to 50 picoseconds apart.

13. The method of claim 7, wherein the amplifying and compressing is done with a optically-pumped-amplifier and air-path between gratings compressor combination, and the sub-picosecond pulses are stretched to between 500 picoseconds and three nanoseconds.

14. A method of ablation laser-machining, comprising the steps of:

generating a train of pulses with more than one amplifiers, each pulse having a pulse-duration of 50 femtoseconds to three picoseconds, with the pulses being at intervals of 1 to 50 nanoseconds; and

directing a beam of the pulses to a work-piece with a pulse-energy-density of 0.1 to 20 Joules/square centimeter to produce at least one hole in the work-piece.

15. The method of claim 14, wherein the pulses are at intervals of 1 to 20 nanoseconds.